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Stakeholder-Driven Energy Storage and Decarbonization Modeling for New Mexico (ESD-NM)

Phase 1 Report

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ABSTRACT

Widespread deployment of energy storage coupled with the decarbonization of electricity generation offers a critical opportunity to achieve a more sustainable, equitable, and resilient electric power system. Using the state of New Mexico as a testbed, Sandia National Laboratories is developing a participatory system dynamics model in close collaboration with the New Mexico Public Regulation Commission, the New Mexico Energy, Minerals, and Natural Resources Department, and the Public Service Company of New Mexico (PNM). The model provides a tool for improving multi-stakeholder understanding, dialogue, and decisions around the role of energy storage in integrated grid planning for deep decarbonization. Specifically, the model enables articulation and exploration of three key questions to inform the implementation of decarbonization objectives pursuant to New Mexico's Energy Transition Act (ETA), which mandates 100% zero-carbon electricity by 2050: First, what are the most important uncertainties associated with future scenarios? Second, what are the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements? Third, what are the tradeoffs associated with these alternative resource portfolios and scenarios? This report documents the development and testing of the Phase 1 model, which is scoped to PNM's service territory and spans 2021-2045. The Phase 1 model uses data and projections from PNM's 2020-2040 Integrated Resource Plan (and other sources) and returns results calibrated to that plan.

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EXECUTIVE SUMMARY

Widespread deployment of energy storage coupled with the decarbonization of electricity generation offers a critical opportunity to achieve a more sustainable, equitable, and resilient electric power system. Realizing this opportunity for a just transition requires addressing complex technology, social, policy, and market dynamics in electric grid regulatory and investment planning processes. With funding from the U.S. Department of Energy Office of Electricity Energy Storage Program under the direction of Dr. Imre Gyuk, Sandia National Laboratories (Sandia) is developing a participatory system dynamics model to improve multi-stakeholder understanding, dialogue, and decisions around the role of energy storage in integrated grid planning for deep decarbonization. Using the state of New Mexico as a testbed, Sandia is working in close collaboration with the New Mexico Public Regulation Commission, the New Mexico Energy, Minerals, and Natural Resources Department, and the Public Service Company of New Mexico (PNM) to develop and test a model

to serve as a forum for stakeholders to compare mental models, and as a methodology for assessing tradeoffs associated with potential policy and investment strategies to enable decarbonization of New Mexico's electricity sector. Specifically, the model enables articulation and exploration of three key questions to inform the implementation of decarbonization objectives pursuant to New Mexico's Energy Transition Act (ETA), which mandates 100% zero-carbon electricity by 2050: First, what are the most important uncertainties associated with future scenarios? Second, what are the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements? Third, what are the tradeoffs associated with these alternative resource portfolios and scenarios?

This report documents the development and testing of the Phase 1 model and interface, which is scoped to PNM's service territory and spans 2021-2045. The key model input variables are scenarios and resource portfolios, and the key model output variables are tradeoffs. Scenarios are combinations of assumptions about uncertain future conditions—including economic/demographic, market/technology, policy/regulatory, and natural resource/climate conditions—that affect the feasibility/cost of alternative resource portfolios or the shape/size of projected load profiles. Resource portfolios are combinations of resources—including generation, storage, demand-side management, and behind-the-meter resources—used to meet projected load profiles over the planning horizon. Tradeoffs are the output metrics associated with alternative resource portfolios under a given scenario—including environmental, utility cost, service quality, customer cost, and socioeconomic impacts.

The Phase 1 model uses data and projections from PNM's 2020-2040 Integrated Resource Plan (and other sources) and returns results calibrated to that plan. Phase 2 modeling will introduce feedbacks, time lags, and other projections to allow stakeholders and modelers to simulate tradeoffs associated with alternative decarbonization strategies for New Mexico's electricity sector. In future phases, the model is well suited to be extended to other states that are developing and implementing ambitious deep decarbonization and energy storage policies.

ACRONYMS AND DEFINITIONS

Abbreviation	**Definition**
BTM	Behind-the-Meter
CapEx	Capital Expenditures
CC	Combined Cycle
CES	Clean Energy Standard
Co-ops	Cooperative Utilities
CT	Combustion Turbine
DOE	Department of Energy
DSM	Demand-Side Management
EMNRD	Energy, Minerals, and Natural Resources Department
ESS	Energy Storage Systems
ETA	Energy Transition Act
EV	Electric Vehicle
IOUs	Investor-Owned Utilities
IRP	Integrated Resource Plan
ITC	Investment Tax Credit
LOLE	Loss of Load Expectation
NARUC	National Association of Regulatory Utility Commissioners
NM	New Mexico

OE	Office of Electricity
OpEx	Operating Expenses
PNM	Public Service Company of New Mexico
PRC	New Mexico Public Regulation Commission
PV	Photovoltaic
RPS	Renewable Portfolio Standards
SAIDI	System Average Interruption Duration Index
Sandia	Sandia National Laboratories
SD	System Dynamics
T&D	Transmission and Distribution
US	United States

1.

INTRODUCTION

Widespread deployment of energy storage coupled with decarbonization of electricity generation offers a pivotal opportunity to transition to a more sustainable, equitable, and resilient electric power system. Realizing this opportunity for a just transition requires addressing complex technology, social, policy, and market dynamics in electric grid regulatory and investment planning processes through a multi-stakeholder systems approach.

Using the state of New Mexico as a testbed, this project is developing a stakeholder-driven decision support model of utility and customer energy storage investment driven by the ambitious decarbonization requirements of New Mexico's Energy Transition Act (ETA) and associated regulatory decision-making. Stakeholders include the New Mexico Public Regulation Commission (PRC), the New Mexico Energy, Minerals, and Natural Resources Department (EMNRD), and the Public Service Company of New Mexico (PNM). This approach extends previous models built using system dynamics (SD) modeling [1, 2] and provides a foundational model to improve multi-stakeholder understanding, dialogue, and decisions around the role of energy storage in integrated grid planning for decarbonization. This model is well suited to be further extended in New Mexico and then applied to other states that are developing and implementing decarbonization and energy storage policies.

This report documents the development and testing of the Phase 1 model and interface, which is scoped to PNM's service territory and spans 2021-2045. The Phase 1 model uses data and projections from PNM's 2020-2040 Integrated Resource Plan (IRP) and other sources and returns results calibrated to the IRP. Phase 2 modeling will introduce feedbacks, time lags, and other projections to allow stakeholders and modelers to simulate tradeoffs associated with alternative decarbonization strategies for New Mexico's electricity sector.

1.1.

Project Funding and Impact

This project is funded by Dr. Imre Gyuk of the U.S. Department of Energy (DOE) Office of Electricity (OE) Energy Storage Program. The Energy Storage Program's mission is to "develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions that will increase the reliability, performance, and competitiveness of electricity generation and transmission in the electric grid and in standalone systems" [3]. The project supports the Energy Storage Program's mission by placing energy storage at the heart of New Mexico's decarbonization conversation and providing a new tool for state policymakers, regulators, utilities and other stakeholders who will need to have robust decision support to achieve decarbonization goals while maintaining resilience and affordability. This tool will enable decision-makers to understand the unique benefits provided by storage technologies while testing alternative policy and technology decisions within a stakeholder-driven, transparent environment. When coupled with highly detailed modeling tools in future iterations, this approach will be able to inform the remaining technical questions which those models must answer—or just as importantly, inform the features that are not needed or are extraneous to the important questions.

1.2.

Report Structure

This report documents the development and testing of the Phase 1 (February 2021-January 2022) model and interface. Section 2 discusses the motivation for the project—including the rapidly evolving decarbonization policy landscape, the centrality of energy storage to meeting decarbonization objectives, and the lack of decision-support tools for enabling utility and customer energy storage investments for decarbonization—and the project's contributions. Section 3 describes the project stakeholders and stakeholder-driven model development process. Section 4 details the objectives and approach of the Phase 1 effort, including the specific policy context for New Mexico, the motivating questions, the spatial and temporal scope, and the priorities and parameters identified by stakeholders. Section 5 describes the Phase 1 model configuration, including capabilities, structure, data, algorithm, and calibration. Section 6 describes the Phase 1 model validation and testing methodology and key outcomes. Section 7 provides a brief conclusion and some details on how the Phase 1 model and interface will be extended and applied in Phase 2 (February 2022-September 2022).

2.

MOTIVATION AND CONTRIBUTIONS

2.1.

Decarbonization Policy Landscape

As the risks associated with unmitigated climate change have become more salient, myriad policies have been enacted to accelerate the transition to a more sustainable energy sector and broader economy. Many of these policies focus on decarbonizing emissions-intensive sectors, including electric power, which is both a critical infrastructure sector and a substantial contributor to economy-wide carbon emissions [4, 5, 6, 7]. At the U.S. federal level, the Biden-Harris administration has set a goal of 100% carbon emissions-free electricity production by 2035 [8]. This federal goal builds on goals at the state and local levels, where there has been substantial progress in enacting policies to address both economy-wide and electricity-sector specific carbon emissions [9, 10].

Across U.S. states and territories, legislation, executive orders, and regulatory proceedings have implemented decarbonization goals by both limiting emissions from electricity power generation and requiring a greater proportion of generation to be provided by renewable or clean energy sources. As Table 1 depicts, as of January 2022, 14 states and territories have adopted zero or net-zero greenhouse gas (mostly carbon emissions) for the power sector and 6 states and territories have economy-wide goals. Additionally, 6 states and territories have 100% renewable energy goals for the power sector [11, 12]. Such policies are complementary to, but often more expansive than, existing renewable portfolio standards (RPS) and clean energy standards (CES), which have played a longstanding role in promoting the development of renewable and clean energy generation sources, respectively, to serve electricity needs across U.S. states and territories. Indeed, some 30 states as well as the District of Columbia, Puerto Rico, and the U.S. Virgin Islands have active RPS or CES requirements [12, 13]. Other state level policies, such those focusing on energy efficiency and energy storage—discussed in Section 2.2—can also serve as enablers of sector-wide decarbonization.

Table 1: U.S. States and Territories with Clean Energy Goals as of January 2022 (Sources: [11, 12], with updates and edits by authors)

Jurisdiction	**Goal (Date)**	**Policy Details and Hyperlinked Source**
California	Electricity: 100% zero CO_2 (2045) Economy: CO_2 neutrality (2045)	2018 executive order (EO B-55-18) set statewide carbon neutrality by no later than 2045 and net negative GHG

		emissions thereafter goal; 2018 legislation (SB 100) extended and expanded RPS.
Colorado	Electricity*: 100% zero CO_2 (2050)	2019 legislation (SB 19-236) codified Xcel's* carbon-free pledge (whose service territory covers ~60% of state load), enforceable subject to technical and economic feasibility.
Connecticut	Electricity: 100% zero CO_2 (2040)	2019 executive order (EO Number 3) set carbon-free electricity by 2040 goal and directed state agency to develop power sector decarbonization plan; prior legislation set economy-wide carbon emissions 80% below 2001 levels by 2050 goal.
District of Columbia	Electricity: 100% RE (2032)	2018 legislation (DC Act 22-583) amended RPS to mandate 100% RE by 2032.
Hawaii	Electricity: 100% RE (2045)	2015 legislation (HB623) set 100% RPS for the electricity sector.

Jurisdiction	**Goal (Date)**	**Policy Details and Hyperlinked Source**
Illinois	Electricity: 100% zero CO_2 (2050)	2021 legislation (SB2408) established 100% clean energy by 2050 goal, with interim targets of 40% by 2030 and 50% by 2040.
Louisiana	Economy: Net-zero GHG (2050)	2020 executive order (EO JBE 2020-18) formed task force to develop roadmap to achieve net-zero economywide GHG emissions by 2050.
Maine	Electricity: 100% RE (2050)	2019 legislation (LD 1494) increased RPS to 80% by 2030 and set 100% RE by 2050 goal; 2019 legislation (LD 1679) set economy-wide goal of 80% cuts to greenhouse gases by 2050.
Massachusetts	Economy: Net-zero GHG (2050)	2020 state agency set net-zero GHG emissions by 2050 goal under the authority of 2008 legislation; same goal was subsequently included in 2021 legislation (Bill S.9).
Michigan	Economy: CO_2 neutrality (2050)	2020 executive order (EO 2020-10) set economy-wide carbon neutrality by 2050 goal and directed state agency to develop plan by end of 2021.
Nebraska	Electricity*: Net-zero CO_2 (2040/2050)	2019, 2020, and 2021 votes by Nebraska Public Power District*, Omaha Public Power District*, and Lincoln Electric System* boards to adopt net-zero emissions goals (Nebraska is the only state served solely by publicly owned utilities and these three utilities serve the vast majority of customers in the state).
Nevada	Electricity: 100% zero CO_2 (2050)	

2019 legislation (SB 358) raised RPS to 50% RE by 2030 and set net-zero emission goal for power sector by 2050.

New Jersey
Electricity: 100% zero CO_2 (2050)
2018 executive order (EO 28) set carbon-free power sector goal and directed PUC to develop Energy Master Plan; 2018 legislation (Bill A-3723) revised RPS to require 35% RE by 2025 and 50% by 2030.

New Mexico
Electricity: 100% zero CO_2 (2045/2050)
2019 legislation (SB 489) set zero-carbon power supply by 2045 for IOUs and by 2050 for co-ops, and amended RPS to 80% RE by 2040 for IOUs and 2050 for co-ops.

New York
Electricity: 100% zero CO_2 (2040)
Economy: Net-zero CO_2 (2050)
2019 legislation (S 6599) set zero-emissions electricity by 2040 requirement and goal of cutting statewide GHG emissions to 40% of 1990 levels by 2030 and 85% by 2050, with net-zero economy-wide carbon emissions by 2050.

North Carolina
Electricity: CO_2-neutrality (2050)
2021 legislation (HB 951) directed PUC to “take all reasonable steps” to achieve a 70% reduction in CO_2 emissions from state electric generating facilities by 2030 and set goal of carbon neutrality by 2050.

Oregon
Electricity: 100% reduction in GHG (2040)
2021 legislation (HB 2021) directed IOUs to reduce GHG emissions from electricity sales to 80% below baseline emissions levels by 2030, 90% by 2035, and 100% by 2040.

Puerto Rico
Electricity: 100% RE (2050)
2019 legislation (SB 1121) set timeline for reaching 100% RE by 2050.

Rhode Island
Electricity: 100% RE (2030)
2020 executive order (EO 20-01) directs state agency to “conduct economic and energy market analysis and develop viable policy and programmatic pathways” to meet 100% RE by 2030.

Jurisdiction
Goal (Date)
Policy Details and Hyperlinked Source

Virginia
Electricity: 100% zero CO_2 (2050)
2020 legislation (SB 851) set zero-carbon emissions by 2045 for Dominion Energy and 2050 for Appalachian Power Company and set goals for 100% RE by 2045 for Phase II utilities and 2050 for Phase I utilities

Washington
Electricity: 100% zero GHG (2045)
Economy: 95% reduction in CO_2 (2050)
2019 legislation (SB 5116) directed utilities to achieve 100% zero-emissions electricity by 2045, with PUC rulemaking and utility plans in process; 2021 legislation (SB 5126) created GHG cap-trade-and-invest system, which along with CES and clean fuel standards will enable 95% reduction in economywide GHG

		emissions by 2050.
Wisconsin	Electricity: 100% zero CO_2 (2050)	2019 executive order (EO 38) directs state energy office to achieve carbon-free power by 2050 goal.

2.2.

Centrality of Energy Storage to Decarbonization

Meeting these ambitious decarbonization and renewables generation goals in the coming decades will require massive energy storage deployments. Long duration energy storage will be particularly critical to decarbonization of electricity generation because it enables the integration of variable renewable energy sources and enables them to provide a larger proportion of overall generation. This will ultimately eliminate reliance on (non-variable) fossil fuel generation sources to serve base loads [14]. Recognizing the criticality of advancing the accessibility of these systems, the U.S. Department of Energy has recently established the Long Duration Storage Energy Earthshot, which seeks to reduce the cost of grid-scale long duration storage (defined as 10+ hours) by 90% in the next decade [15].

State policies have also played a critical role in advancing the development and implementation of energy storage systems [16, 17]. There are various policy actions that can promote energy storage adoption, including requiring inclusion of storage in utility integrated resource plans, (IRPs), financial incentives (e.g., tax credits, multiple use applications, and net metering policies. As Table 2 depicts, as of January 2022, 9 states have established energy storage procurement targets, goals, or mandates.

Table 2: U.S. States with Energy Storage Requirements as of January 2022 (data compiled by authors, leveraging the following sources: [18, 16, 19])

Jurisdiction	**Goal (Date)**	**Policy Details and Hyperlinked Source**
California	1,825 MW (2020)	2013 CPUC rule (Rulemaking 10-12-007) pursuant to 2010 legislation (AB 2514) sets 1,325 energy storage procurement target for IOUs, with targets for non-utility LSEs at 1% of annual load (Rulemaking 10-12-007); 2017 CPUC rule (Rulemaking 15-03-011) pursuant to 2016 legislation (AB 2868) requires IOUs to propose programs and investments up to 500 MW of BTM energy storage resources.
Connecticut	1,000 MW (2030)	2021 legislation (SB 952) establishes target of 1,000 MW energy storage by 2030, with interim targets of 300 MW by 2024 and 650 MW by 2027.
Maine	400 MW (2030)	2021 legislation (LD 528) establishes goal of 400 MW by 2030 with interim goal of 300 MW by 2025.
Massachusetts	1,000 MWh (2025)	2018 legislation (HB 4857) establishes target of 1,000 MW energy storage by 2025 building on 2016 legislation (HB 4568) that resulted in 2017 goal of 200 MW by 2020.
Nevada	1,000 MW (2030)	2020 PUC rule (R106-19) pursuant to 2017 legislation (SB 204) establishes target of 1,000 MW by end of 2030, with interim targets starting at 100 MW by 2020 and increasing biennially by 100 MW until final goal is met.
New Jersey	2,000 MW (2030)	

2018 legislation (A.B. 3723) establishes goal of 2,000 MW by 2030 with interim goal of 600 MW by 2021.
New York
3,000 MW
(2030)
2018 PSC order (CASE 18-E-0130) pursuant to 2017 legislation (PSL §74) establishes statewide energy storage procurement mandate of 3,000 MW by 2030 with interim objective of 1,500 MW by 2025; 2022 announcement of plans to double NY's energy storage deployment target from 3,000 MW to at least 6,000 MW by 2030.
Oregon
>10 MWh
(2020)
2015 legislation (HB 2193) establishes a 5 MWh minimum (up to 1% of 2014 peak load) energy storage procurement mandate for OR's two largest IOUs by 2020, and then no more than the equivalent to 1% of their peak load each year thereafter.
Virginia
3,100 MW
(2035)
2015 legislation (SB 851) establishes storage procurement mandate of 2,700 MW for Dominion Energy by 2035 (with interim requirements of 250 MW by 2025 and 1,200 MW by 2030) and 400 MW for Appalachian Power Company by 2035 (with interim requirements of 25 MW of by 2025 and 125 MW by 2030).

2.3.

Relevant Literature, Existing Tools, and Gaps

Despite these clear electricity decarbonization and energy storage policy trends, methodologies for exploring the most effective technical pathways, for educating stakeholders, and for achieving buy-in for preferred strategies are underdeveloped in both the literature and in practice. This project brings together several modeling approaches to address these gaps.

2.3.1. Simulation Models for Exploring Complex System Behaviors: (Participatory) System Dynamics (SD)

The project's approach is grounded in SD, a simulation modeling methodology for exploring complex system behaviors. The SD methodology has been used in electricity-focused applications with notable success, such as elucidating failures of the California electricity deregulation experiment in the late 1990s, supporting energy storage decisions in Ontario, and holistic energy system planning in Australia [20, 21, 22]. More recently, SD has been used to explore the economic and environmental impacts of alternative renewable portfolio standards for U.S. states [23]. Together, these projects provide critical model structures describing long-term behavior of the electricity sector across various market and regulatory contexts. A sub-field of SD, referred to as participatory SD involves developing SD models through a collaborative, stakeholder-driven approach. Participatory SD modeling has a rich history over the last 20 years—with Sandia National Laboratories at its beginnings—in analyzing and addressing complex multi-stakeholder problems by providing tools to increase stakeholder understanding of system behavior, feedbacks, time lags, non-linearities, interconnections, and interdependencies [24, 25, 26, 27].

A key benefit of participatory SD modeling is the ability to create a forum for stakeholder discussions and decisions, which is facilitated by the speed at which models are able to run. For example, the model described in this report is designed to be relatively coarse-grained—spanning nearly 25 years and an entire utility service territory—and runs in a matter of seconds. It enables stakeholders to use virtual slider bars, buttons, and other objects in the model interface to design and simulate alternative future scenarios and resource portfolios to gain insight into uncertainties and tradeoffs.

2.3.2. Optimization Models for Power System Planners and Operators: Capacity Expansion and Production Cost Modeling

Two dominant modeling approaches used in electricity system planning and operation are capacity expansion models and production cost models. Capacity expansion models are used to evaluate alternative generation and transmission capacity investments across potential future scenarios over a relatively long-time horizon. These models are useful for exploring the impacts of alternative future scenarios (e.g., demand, technology and commodity costs, policy and regulatory environment) on generation and capacity, and can be implemented at the national level or utility service territory level.

As such, utilities often use capacity expansion models to inform their IRPs. Production cost models simulate the operation of a given system over a shorter time horizon and at a higher resolution than capacity expansion models. Production cost models are used to assess the operational, cost, emissions, and selected reliability implications of capacity changes (e.g., adding/retiring generation, storage, demand-side-management) within a given system and are generally implemented at the utility service territory level [28].

Capacity expansion and production cost modeling approaches result in precise outputs to guide utility decision-making. However, they are computationally intensive and thus do not run sufficiently fast to enable a forum for real-time multi-stakeholder dialogues, nor are they designed to represent nonlinear feedback mechanisms that drive system behavior over time and may be relevant for policymakers and other stakeholders. As such, these modeling approaches may be coupled with SD modeling to facilitate multi-stakeholder dialogue and inform decisions related to electricity sector decarbonization and accompanying technology, policy, and market dynamics.

2.3.3. Training Tool for State-Level Electricity Regulators and Policymakers: MegaModel

The National Association of Regulatory Utility Commissioners (NARUC) and Energy Innovation developed “MegaModel,” a training simulation for state energy regulators, legislators, energy officials, and other policymakers. MegaModel allows users to explore utility performance—as measured by “customer bills, earnings per share, environmental performance, and reliability”—under alternative business and regulatory models—including “vertically integrated cost of service, vertically integrated performance-based, restructured cost of service, and restructured performance-based” [29].

MegaModel has generated invaluable insights and discussion among regulators and other state-level electricity policymakers. However, as an Excel-based tool that relies on a highly aggregated and simplified linear model, MegaModel is not able to incorporate results from sophisticated grid models (such as those described in Section 2.3.2) nor capture the important nonlinear feedback mechanisms that drive system behavior over time. As such, there is an opportunity to build upon the success of MegaModel by developing a model that integrates more granular approaches and represents complex system dynamics and can be applied in a multi-stakeholder training environment in partnership with NARUC and other organizations.

2.4.

Project Contributions

This project develops a participatory SD model to represent long term electricity system behavior that is informed by both robust engagement with diverse stakeholders and incorporation of capacity expansion and production cost modeling approaches and data. The resulting model both provides a forum for various stakeholders to compare their mental models of future states and a novel methodology for assessing the tradeoffs associated with potential policy and investment strategies. With future associated efforts, the project plans to bring in more highly detailed and sophisticated modeling platforms, such as production cost models and resilience models, to inform the SD model. If successful, the resulting model will enable more rapid and transparent state-level discussion of the most effective energy storage-relevant policies and technology decisions to achieve decarbonization of the energy sector. The buy-in and enrichment of mental models associated with participatory modeling of this type allows stakeholders to identify and assign relative quantification to issues that matter most to key performance indicators.

Collectively, this approach will enable the project to make several contributions. First, it assembles key energy stakeholders from across state government agencies, utilities, academia, industry, and nongovernmental organizations to identify data availability, data gaps, system structure, and modeling objectives. Second, with stakeholder supervision, it builds a decision support model in a SD modeling setting that allows users to experiment with different future energy storage-inclusive resource portfolios, and to explore how different resource storage configurations and scenarios might affect key metrics of interest. Third, it uses the model to demonstrate preferred strategies for energy storage deployment to the public and other stakeholders, educate them on energy dynamics, pursue buy-in and build consensus from across the stakeholder community, and to provide insight for relevant policy processes. Fourth, it uses modeling results to drive inputs to more highly resolved modeling, such as capacity expansion or production cost modeling. Fifth, it demonstrates a pathway to regional application or extension to other states.

3.

STAKEHOLDERS AND ENGAGEMENT PROCESS

This project employs participatory SD modeling, which entails a collaborative process in which key stakeholders drive the development, refinement, and implementation of the model. Stakeholders are instrumental in defining the key questions, dynamics, and outcomes that the model will address. This approach has several virtues. First, it provides modelers with a more complete and balanced understanding of energy system dynamics and challenges in a given jurisdiction by incorporating a range of viewpoints and interests. Second, it provides modelers with better understanding of the structure and dynamics of the system and more and better data, since different stakeholders have different perspectives on the system and access to different data sources. Third, by participating in the modeling process, stakeholders gain an understanding of how the model was assembled, its strengths and weaknesses, and how it should and should not be used. Fourth, stakeholders have a sense of ownership in the model, which allows them to be advocates for the modeling and the results with other stakeholders.

3.1.

Stakeholder Advisory Group

Phase 1 of this project was guided by a stakeholder advisory group representing three key entities involved in New Mexico's transition to a decarbonized electric power sector: the state's electric utility regulatory commission (PRC), the state energy office (EMNRD), and the state's largest electric utility (PNM).

The PRC is an independent regulatory agency with jurisdiction over utilities, telecommunications, and transportation industries in New Mexico [30]. With respect to utilities, the PRC has authorities over natural gas utilities, propane utilities, investor-owned water and sewer utilities, and investor-owned electric utilities (IOUs) and cooperative electric utilities (co-ops) [30]. PRC Chair (during Phase 1 of this project) and Commissioner (District 5) Stephen Fischmann and PRC Vice-Chair and Commissioner (District 1) Cynthia Hall, as well as their staff member Collin Gillespie, served on the stakeholder advisory committee.

The EMNRD is a state agency with broad jurisdiction over New Mexico's energy and natural resources [31]. EMNRD's Energy Conservation and Management Division develops energy policies and programs related to renewable energy, energy efficiency, and grid modernization [31]. Dr. Jacqueline Waite, Clean Energy Program Manager in the Energy Conservation and Management Division of EMNRD, served on the stakeholder advisory committee.

PNM is an IOU and New Mexico's largest energy provider, serving some 525,000 residential and business customers [32]. PNM's service territory covers greater Albuquerque, Rio Rancho, Los Lunas, Belen, Santa Fe, Las Vegas, Alamogordo, Ruidoso, Silver City, Deming, Bayard, Lordsburg, and Clayton, as well as New Mexico tribal communities of the Tesuque, Cochiti, Santo Domingo, San Felipe, Santa Ana, Sandia, Isleta, and Laguna Pueblos [32]. Nick Phillips, PNM's Director of Integrated Resource Planning, served on the stakeholder advisory committee.

3.2.

Project Team

Recognizing the complex dynamics involved in electric grid regulatory and investment planning processes for deep decarbonization, the project team by design included a broad range of disciplinary and substantive expertise and experience. The project team consisted of personnel from three organizations, including Sandia (Dr. Bobby Jeffers, Dr. Howard Passell, Robert Taylor, Dr. Vincent Tidwell, Will McNamara), MindsEye Computing, LLC (Jake Jacobson and Len Malczynski),

and Bosque Advisors (Dr. Mercy Berman DeMenno). The project team spans multiple disciplines—including systems science, power systems engineering, hydrology, ecology, statistics, economics, and political science—bringing to bear a well-rounded understanding of energy and electric grid regulatory and investment planning processes, climate change and deep decarbonization, and the attendant technology, social, policy, and market dynamics.

3.3.
Stakeholder Engagement Approach

The project team met with stakeholders throughout the project for both regularly scheduled progress meetings and periodic stakeholder workshops. For the first half of the project, the project team met with the stakeholder advisory group weekly and for the second half of the project it met biweekly for regularly scheduled progress meetings. These meetings were essential for developing the motivating analytical questions, translating questions in model objectives, prioritizing key input and output variables, understanding the system structure and dynamics therein, identifying data and data gaps, and ensuring that stakeholders had ownership over the model development process. There were also ad hoc meetings with selected members of the stakeholder advisory group to enable more detailed discussions of the model structure and data sources.

In addition to these regular and mostly virtual meetings, there were several longer in person workshops which were used to demonstrate the model, develop scenarios, and refine the model interface. The first in person meeting of the stakeholder advisory group was held in September 2021 in Santa Fe, NM. This meeting was used to build a mutual understanding of the model, review uncertainty and resource input variable assumptions, identify scenarios for future exploration, and discuss tradeoff output metrics. Specifically, the discussion and feedback centered on the following set of questions:

- What are alternative future scenarios and how might the model best expose associated uncertainties?
- What resource portfolios would you most like to explore, and under which scenarios?
- What tradeoff variables do we think will conflict with each other? How might the model best expose these tradeoffs?
- Does the interface provide adequate understanding of the inputs and outputs? In which inputs and outputs are we most/least confident (and why)?

The September 2021 in person meeting helped solidify a high degree of consensus around the key input and output variables, particularly the tradeoff metrics. It also revealed that among the potential scenarios, those related to electrification as part of deep decarbonization, and particularly vehicles electrification, are of the greatest interest to stakeholders. Related, tradeoff variables that capture the effects of electrification on total energy costs (i.e., wallet share) are also of interest.

In response, a second in person stakeholder meeting, held in December 2021 in Albuquerque, NM focused on demonstrating the Phase 1 model capabilities and discussing the Phase 2 priorities. Specifically, the model demonstration focused on reviewing the base case and validating the results followed by exploration of alternative EV adoption scenarios and resource portfolios. Questions addressed included:

- Which results are the most or least interesting, and why?
- What types of decisions might the results inform? How can the model be more useful for decision making?
- What additional modeling questions or sensitivity analyses would be of interest for the Phase 1 model? Who else would benefit from a model demonstration?
- How could the interface be more user-friendly? What additional model documentation could we provide?

During this meeting and in follow-on engagements the stakeholders also provided feedback on the Phase 2 model expansion, including the spatial and temporal scope, scenarios, resources portfolios, and tradeoff metrics. Moreover, feedback was collected on which aspects of the stakeholder-driven model development process worked well in Phase I and how processes and outcomes could be improved in Phase 2 as well as other stakeholders that might be engaged in Phase 2. This regular and in-depth engagement ensured that stakeholders drive the development, refinement, and implementation of the model.

4.
PHASE 1 OBJECTIVES AND APPROACH

This project seeks to develop a decision support model of utility and customer energy storage investment driven by ambitious decarbonization requirements and associated regulatory decision-making. Using New Mexico as a testbed, the goal of the first phase was to develop and test a baseline version of the SD model that enables stakeholders to explore alternative pathways to achieve electricity decarbonization. Stakeholders representing organizations that may be end-users of the model were directly involved in the iterative design, development, and validation of the model. This resulting Phase 1 model enables stakeholders to evaluate alternative storage-inclusive resource portfolios for achieving decarbonization targets and provides the foundation for further development and refinement in Phase 2 as well as extension to other states.

4.1.
New Mexico Energy Transition Act (ETA)

Given the initial application to the state of New Mexico, decarbonization targets refer to those established in the ETA. Passed in 2019, the ETA requires IOUs and co-ops to provide retail electricity customers in New Mexico with 100% zero-carbon resources by 2045 and 2050, respectively.[1] The ETA also amends the state's RPS to require electricity for customers in New Mexico to be generated by at least 80% renewable resources by 2040 for IOUs and 2050 for co-ops.[2] The ETA includes an innovative financing mechanism to facilitate the transition away from carbon-intensive generation sources—the Energy Transition Bond—and utilities that utilize this mechanism are also subject to a carbon intensity requirement. These decarbonization targets and their associated timelines and metrics are depicted in Table 3.

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[1] For both IOUs and co-ops, the ETA defines "zero carbon resource" as "an electricity generation resource that emits no carbon dioxide into the atmosphere, or that reduces methane emitted into the atmosphere in an amount equal to no less than one-tenth of the tons of carbon dioxide emitted into the atmosphere, as a result of electricity production" (NM Stat § 62-16-3 (2019) & NM Stat § 62-15-37 (2019)). Although the requirement does not come into effect until 2040 for IOUs, the ETA states that "reasonable and consistent progress shall be made over time toward this requirement" (NM Stat § 62-16-4 (2019)).

[2] For IOUs, the ETA defines "renewable energy resource" as "the following energy resources, with or without energy storage: (1) solar, wind and geothermal; (2) hydropower facilities brought in service on or after July 1, 2007; (3) biomass resources, limited to agriculture or animal waste, small diameter timber, not to exceed eight inches, salt cedar and other phreatophyte or woody vegetation removed from river basins or watersheds in New Mexico; provided that these resources are from facilities certified by the Energy, Minerals and Natural Resources Department to: (a) be of appropriate scale to have sustainable feedstock in the near vicinity; (b) have zero life cycle carbon emissions; and (c) meet scientifically determined restoration, sustainability and soil nutrient principles; (4) fuel cells that do not use fossil fuels to create electricity; and (5) landfill gas and anaerobically digested waste biogas" (NM Stat § 62-16-3 (2019)).

For co-cops, the ETA defines "renewable energy resource" as "electric or useful thermal energy: (1) generated by use of the following energy resources, with or without energy storage and delivered to a rural electric cooperative: (a) solar, wind and geothermal; (b) hydropower facilities brought in service on or after July 1, 2007; (c) other hydropower facilities supplying no greater than the amount of energy from hydropower facilities that were part of an energy supply portfolio prior to July 1, 2007; (d) fuel cells that do not use fossil fuels to create electricity; (e) biomass resources, limited to agriculture or animal waste, small diameter timber, not to exceed eight inches, salt cedar and other phreatophyte or woody vegetation removed from river basins or watersheds in New Mexico; provided that these resources are from facilities certified by the energy, minerals and natural resources department to: 1) be of appropriate scale to have sustainable feedstock in the near vicinity; 2) have zero life cycle carbon emissions; and 3) meet scientifically determined restoration, sustainability and soil nutrient principles; and (f) landfill gas and anaerobically digested waste biomass; and (2) does not include electric energy generated by use of fossil fuel or nuclear energy" ((NM Stat § 62-15-37 (2019)).

Table 3: Decarbonization Targets Established in New Mexico's Energy Transition Act

2015
2020
2025
2030
2035
2040
2045

→

2050
Renewable Resources
(% retail sales to NM customers)
IOUs
15%
20%

40%
50%
80%
Co-ops
5%
10%
40%
50%
80%
Zero
Carbon
Resources
(% retail
sales in NM)
IOUs
100%
Co-ops
100%
Carbon
Intensity
(average
generation
CO_2 for NM
customers)
Utilities
Issuing
Energy
Transition
Bonds
400
lbs./MWh
(2023)
200
lbs./MWh
(2032→)

The ETA mandates a transition to a more environmentally sustainable electric power system in New Mexico that maintains electricity affordability and reliability for customers and promotes economic development, particularly within communities affected by fossil fuel plant retirements. New Mexico is among only 10 U.S. states in which electric utility regulators are empowered to evaluate non-energy economic impacts (e.g., jobs, taxes) in decision-making [33, 34], providing a unique opportunity to consider the energy equity and justice implications of alternative decarbonization strategies pursuant to the ETA. The myriad stakeholders involved in the energy transition—including electric utility regulators, utilities, and state energy policymakers, and end users—have different criteria by which they assess and prioritize potential strategies to meet the goals established in the ETA. Moreover, the realization of a given decarbonization scenario is associated with substantial uncertainty with respect to technology, market, policy, and environmental dynamics.

4.2.

Framing and Analysis Questions

The first phase of the model enables stakeholders to explore alternative pathways to achieve the electricity decarbonization targets established in the ETA. Model simulations can support stakeholder discussions and decisions related to ETA implementation by providing insight into three key questions.

- First, what are the most important uncertainties associated with future scenarios?
- Second, what are the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements?
- Third, what are the tradeoffs associated with these alternative resource portfolios and scenarios?

These questions lead to a high-level description of the model's necessary inputs and outputs, as depicted in Figure 1. First, the model must allow users to construct scenarios to describe future states of the world. Scenarios, made with key model inputs, are combinations of assumed values for

the selected uncertainty variables that affect the feasibility or cost of alternative resource portfolios and the shape or size of projected load profiles. Second, the model must allow users to select combinations of electricity resources to meet projected load profiles over the planning horizon.

Resource portfolios, also made with key model inputs, are combinations of these resources. Third, the model must quantify the tradeoffs associated with alternative resource portfolios for selected scenarios. Tradeoff metrics, which are the key model output, reflect both the ability to meet the ETA requirements and other outcomes of interest to model users.

Figure 1: High-Level Model Schematic

4.3.

Spatial and Temporal Scope

Given the structure of New Mexico's electric power sector—with three large IOUs (PNM, El Paso Electric, and Excel Energy) and 16 smaller electric distribution co-ops serving rural communities—and the variation in regulatory requirements for IOUs and co-ops (including pursuant to the ETA), the project chose to start with the state's largest IOU to enable efficient development of a baseline version of the model. PNM is the state's largest utility, and its service territory covers a substantial portion of the state both in terms of geography and load. Moreover, PNM is currently the only utility subject to the third decarbonization target—carbon intensity—established in the ETA. In addition, PNM has made a corporate commitment to reach the ETA's zero carbon resource standard by 2040, 5 years ahead of the statutory requirement. Finally, PNM recently completed its 2020-2040 IRP, which articulates how it plans to evolve its resource portfolio to meet the ETA requirements, the ways in which these alternative portfolios affect reliability and costs, and the sensitivity of these portfolios to potential future conditions. The IRP provides a useful set of data and baseline assumptions against which the model can be calibrated to enable verification and validation [35, 36].

Thus, in Phase 1, the spatial scope for the model is PNM's service territory, and the temporal scope is 2021-2045. In future phases, and depending on stakeholders' priorities, the model could incorporate other IOUs as well as co-ops, the spatial scope could be expanded to encompass the entire state of New Mexico, and the temporal scope could be extended through 2055 (five years after the zero-carbon resource requirement for co-ops, to account for any lagged effects on key output metrics).

4.4.

Variables

After selecting the framing questions and defining scope, the project team engaged with stakeholders to understand their respective priorities underscoring each question and to translate these priorities into variables that could be represented in the model. Inherent in the three framing questions are concepts whose definitions may vary based on a given stakeholder's values and incentives. Collaboratively defining these concepts, which included eliciting underlying priorities translating this input into categories and model variables, was essential to the development of a model that is decision-useful for stakeholders.

4.4.1. Scenarios

The first question—What are the most important sources of uncertainty associated with future scenarios? —required defining the categories of uncertainties associated with future conditions that could affect the feasibility or cost of alternative resource portfolios and the shape or size of project load profiles. Stakeholders identified four broad categories of uncertainties, which comprise the dimensions of scenarios: economic/demographic, technology/market, policy/regulatory, and natural resource/climate conditions. Based on input from stakeholders, data availability, and relevance to key questions, the team selected from this broader list the set of scenario variables to be included in Phase 1, as depicted in Figure 2.

Economic and demographic uncertainties reflect how changes in economies and populations—including population and energy intensity growth, employment, income, economic development, and electrification of vehicles and buildings— affect the shape and size of load profiles. Among these variables, stakeholders were most interested in those related to electrification, particularly electric vehicles (EV). As such, in Phase 1, the model incorporated population and energy intensity variables to reflect overall load growth as well as EV adoption rate to reflect the effects of vehicle electrification on load. In future phases, economic and demographic scenario variables may be expanded to include building electrification and various economic development scenarios.

Technology and market uncertainties reflect how available commodities, technologies, and infrastructures may evolve. In Phase 1, the model incorporates natural gas and hydrogen fuel variables to represent how changes in commodity prices affect the cost and feasibility of alternative resource portfolios. In future phases, these variables may be expanded to reflect other commodity and technology prices as well as grid infrastructure developments. Moreover, the effects of technology and market dynamics on load—for example, due to the relative costs of heating fuels versus electricity—could be included in future phases.

Policy and regulatory uncertainties refer to the effects of a broad set of alternative policy choices and designs on both utility and consumer behavior, and in turn both the shape and size of load profiles and the feasibility of resource portfolios. Such policies are wide-ranging and could include various rate design, carbon pricing, and tax incentives. Understanding how different policy designs affect utility incentives and customer behavior could be a key focus of the second phase of the model; for example, the model might couple the effects of behind-the-meter (BTM) incentives with alternative rate design and cost allocation approaches to explore dynamics related to grid defection.

Natural resource and climate uncertainties refer to how a changing environment—including temperature, global horizontal irradiance, water availability, and wind patterns—may affect the feasibility and cost of alternative resource portfolios. For example, global horizontal irradiance and wind patterns affect the productivity of wind and PV, respectively. While these environmental conditions may be incorporated into future phases of the model, they were not prioritized for inclusion in Phase 1 given the scope and structure of the model and relative importance of other uncertainty variables for stakeholders.

Figure 2: Phase 1 Scenarios Categories and Variables

4.4.2. Resource Portfolios

The second question—What are the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements? —required defining the categories of resources that comprise a resource portfolio. Stakeholders identified the key resource categories as utility electricity generation, storage, and demand-side management (DSM) resources, as well as BTM electricity generation and storage resources. Within these categories, the stakeholder team identified a wide range of resources based on current and potential future technologies, as depicted in Figure 3. Based on input from stakeholders, data availability, and relevance to key questions, the team selected from this broader list the set of generation, storage, demand-side management, and BTM resource variables to be included in Phase 1.

Generation resources refer to utility-scale generation assets, which can encompass various asset types, capacities, and configurations (e.g., centralized vs. decentralized). In Phase 1, the selected resource variables represent the generation sources included in PNM’s IRP: coal, nuclear, combustion turbine (CT) and combined cycle (CC) natural gas, geothermal, solar photovoltaic (PV), and wind. These resources include both renewable (i.e., geothermal, PV, wind) and non-renewable (i.e., coal, nuclear, natural gas) resources, as defined by the ETA. Future iterations of the model could incorporate a broader range of generation resources, such as biomass.

Energy storage resources refer to utility-scale energy storage assets, represented as technology types, capacities, durations, and speeds. The inclusion of energy storage is a critical contribution, and indeed motivation, of this model; however, it is also the resource that is subject to perhaps the greatest uncertainty because of the rapidly evolving storage landscape and the associated feasibility and costs of alternative storage technologies. To balance the need to include technology-specific characteristics in the model with the uncertainty regarding their availability, the Phase 1 model includes the two types of storage—short duration battery storage and long duration hydrogen storage—which represent not only different durations, but also different technology readiness levels and associated uncertainties around costs. Future iterations of the model could incorporate a broader range of storage resources, such as longer duration batteries and pumped hydro.

DSM resources refer to utility-led energy efficiency and demand response resources, which may encompass a wide range of technologies, programs, and services as defined in applicable planning

regulations. Consistent with PNM’s IRP and the PRC’s IRP rules, demand response is defined as “a resource comprising programs that compensate electricity users in exchange for the ability to interrupt or reduce their electric consumption when system demand is particularly high and/or system reliability is at risk” whereas energy efficiency is defined as “measures, including energy conservation measures or programs that target consumer behavior, equipment, or devices to result in a decrease in consumption of electricity without reducing the amount or quality of energy services [35, pp. B-2]. For simplicity, in the first phase of the model DSM is a composite resource variable representing both energy efficiency and demand response resources.

BTM resources refer to customer-owned generation and storage assets that are installed behind the utility’s electricity meter. While utility planning processes generally treat BTM resources as exogenous, future phases of the model could allow users to explore BTM generation and storage resources—including potential usage of electric vehicles for storage as well behavioral dynamics related to BTM investment decisions.

Figure 3: Phase 1 Resource Portfolio Categories and Variables

4.4.3. Tradeoffs

The third question—What are the tradeoffs associated with these alternative resource portfolios? —required defining the categories of metrics that could be used to quantify the performance of alternative resource portfolios vis-à-vis stakeholders’ priorities, and thus allow stakeholders to assess the attractiveness of alternative strategies. Drawing on the intent of the ETA as well as the respective mandates and priorities of each represented organization, the stakeholders identified the key tradeoffs as environmental, utility cost, service quality, customer cost, and socioeconomic impacts. A key advantage of the stakeholder-driven modeling process is the ability to select tradeoff metrics that reflect the diverse values of stakeholders involved in, and affected by, the electricity system and broader energy system. Based on input from stakeholders, data availability, and relevance to key questions, the team selected from this broader list the set tradeoff variables to be included in Phase 1, as depicted in Figure 4.

Environmental tradeoffs refer to the impact of alternative resource portfolios on the environment. In Phase 1, metrics focus on compliance with the ETA’s requirements related to carbon dioxide emissions from generation—with metrics for both the percentage of generation from zero-carbon resources and portfolio carbon intensity—and generation from renewable energy sources. Together, these metrics enable assessment of compliance with the ETA over time (see Table 3) as well as an assessment of cumulative portfolio carbon emissions. In future phases the project could incorporate carbon emissions across sectors (e.g., electricity, buildings, transportation)—to inform deep decarbonization strategies—as well as broader range of greenhouse gas emissions (e.g., methane) and other environmental impacts (e.g., water and land use) for electricity generation.

Utility cost tradeoffs refer to utilities’ costs of service for a given resource portfolio in a given future scenario. In Phase 1, the utility cost metrics focus on capital expenditures (CapEx) and operating expenses (OpEx), which enables an assessment of the present value of costs for a given portfolio (discounted using the weighted average cost of capital) and the relative contributions of CapEx and OpEx to utility costs over time. In the Phase 1 version of the model, it is assumed that the utility owns all generation assets, and that CapEx is fully allocated the first year of operation for each new asset built after 2021. CapEx includes an investment tax credit (ITC) for all new battery capacity added after 2021 (the ITC has a tiered approach, 30% credit in 2021, 26% in 2026, and 10% in 2030). For OpEx, costs are the sum of annual fuel costs plus operation and maintenance costs. In future phases, additional cost considerations could be added to align with a more complete revenue requirement metric that reflects utility procurement strategies, accounting approaches, and financing mechanisms.

Service quality refers to the reliability, safety, and resilience of electricity service. While some dimensions of service quality, such as reliability standards for both transmission and distribution, are well institutionalized, others are more nascent, such as resilience metrics which are an active area of research [37]. In Phase 1, the service quality tradeoffs focus on two key reliability metrics, MWh of unserved load and spinning reserve margin adequacy, which allows for an assessment of comparative performance of alternative resource portfolios with respect to reliable service delivery. Spinning reserve is generation capacity that is online but unloaded and can respond within 10 minutes to compensate for generation outages. Spinning reserve margin is put in place to assure that the system can handle moderate loss-of-load scenarios. The spinning reserve goal in the Phase 1 model is ~20% of online capacity; in other words, there needs to be an additional 20% of generation that can be supplied in a very short time (seconds) beyond the amount of energy production that is serving load. In future phases, additional metrics may be introduced to both expand reliability

assessments and consider other dimensions of service quality. For example, while reliability metrics are useful for assessing the effects of more chronic climate-related hazards, more acute climate-related hazards (e.g., natural disasters that lead to long duration, widespread outages) necessitate the consideration of resilience metrics.

Customer costs refer to the costs incurred by ratepayers for a given resource portfolio in a given future scenario. Customer costs were not calculated in Phase 1, but in subsequent phases customer costs could include aggregate electricity rates (i.e., the average rate across residential, commercial, and industrial customers) as well as transportation and heating costs. The latter allows for an assessment of electricity and transportation “wallet share” in alternative vehicles and building electrification scenarios, thus providing legibility into customer costs associated with deep decarbonization scenarios, including disaggregated by socioeconomic status to enable an assessment of energy burden. Moreover, customer returns on BTM investments could be incorporated into future phases to allow endogenous exploration of customer investments and potential grid defection. Finally, alternative cost allocation principles could be explored in future model scenarios, which would enable assessment of the effects of various ratemaking strategies and resource portfolios on customer costs [38].

The final category of tradeoffs encompasses the broad range of potential socioeconomic outcomes associated with alternative transition pathways, which include effects on employment, income, economic output, economic diversification, tax revenue, and energy equity and justice. While such metrics were recognized as critically important by all stakeholders and the project team—and indeed as noted above the ETA is relatively unique in empowering the PRC to consider non-energy economic impacts—it was determined that operationalizing them in a meaningful way in the model would require both geographic expansions to include the entire state of New Mexico as well as disaggregation to the county level. As such, these socioeconomic tradeoffs could be implemented in future phases of the model.

Figure 4: Phase 1 Tradeoffs Categories and Variables

5.

PHASE 1 MODEL CONFIGURATION

5.1.

Capabilities

The Phase 1 model enables users to complete the following steps, moving left to right in the model schematic in Figure 5 below and drawing on the discussion of variables in Section 4.4. First, it allows users to construct scenarios to describe future states of the world. Second, it allows users to explore how alternative scenarios affect projected load profiles as well as the feasibility and costs of alternative resource portfolios. Third, it allows users to select resource portfolios, which are combinations of electricity resources used to meet projected load profiles over the planning horizon. Fourth, it provides users with a quantification of the tradeoffs associated with alternative resource portfolios for selected scenarios (together, resources portfolios and scenarios are referred to as “cases”). Tradeoff metrics, which are the key model output, reflect both the ability to meet the ETA requirements and other outcomes of interest to model users, including utility cost and service quality.

Figure 5: Full Detail Model Schematic

5.2.

Structure and Documentation

The SD modeling paradigm was used as a framework for the model, and operations research and accepted methods of computing resource dispatch and production costing were also employed. The model was built in Powersim Studio 10 and a user interface was added, and the resulting application runs in Powersim Studio 10 Cockpit.[3] The model is documented internally by dividing the model into modules, the layout of variables in each module, specific documentation of specific variables, and the naming convention used to name variables. As described in Appendix A, the model is documented externally according to SD model documentation conventions [39, 40, 41].

The model operates on a monthly timestep, using an "average" day for each month, and projects resource portfolios to meet forecasted load profiles on a monthly timescale during the planning horizon.

5.3.

Scope and Data

Climate change is a global problem and deep decarbonization is shaped by policy decisions at the international, national, regional, and local levels. Given the focus on the U.S. electric power sector and the comparative maturity of state decarbonization and energy storage policies, the focus of this model is one U.S. state–New Mexico-- with an ambitious decarbonization target. The Phase 1 model's spatial scope is PNM's service territory, and the temporal scope is 25 years, 2021-2045 (Section 4.3).

The variables included in the model fall into one or more of these categories: variables that represent data input (exogenous), variables used for calculations (endogenous), variables created to build a user interface, and variables used for debugging and model quality checking (typically deleted from the final version). The key input and output variables are summarized in Table 4. Data to populate these variables came from several sources: PNM's 2020-2040 IRP report, appendices, and underlying datasets [35, 36] and the National Renewable Energy Laboratory's electricity technology cost database and analyses [42, 43]. The model is constrained by the availability of data therefore, the time unit for analysis is one year (see Appendix A for more details).

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[3] There is a free download for Powersim Studio 10 Cockpit, details available upon request.

Table 4: Phase 1 Variables

Categories		**Variables**
Scenarios	Economic/Demographic	Population and Energy Intensity Growth
		EV Adoption
	Technology/Market	Natural Gas Prices
		Hydrogen Prices
Resources	Generation	Coal
		Nuclear
		Natural Gas (CT, CC)
		Geothermal
		Photovoltaics
		Wind
	Storage	Battery (Short Duration)
		Hydrogen (Long Duration)
	Demand-Side Management	Energy Efficiency
		Demand Response
Tradeoffs		

Environmental
Total Carbon Emissions
Zero Carbon Resource Generation
Renewables Generation
Portfolio Carbon Intensity
Utility Cost
Present Value of Total CapEx and OpEx
CapEx
OpEx
Service Quality
MWh of Unserved Load
Spinning Reserve Margin Adequacy
O
th
e
r

- T&D Loss Rate
- Discount Rate
- Hydrogen Draw Time

5.4.
Dispatch Algorithm

There are multiple sources of energy generation that need to be dispatched to meet customer loads. These include dispatchable energy sources, such as nuclear, coal, natural gas CC, natural gas CT, and geothermal, as well as intermittent energy resources including PV and wind. In addition to more intermittent generation, the latter also have capacity limitations and distinctive cost factors. Storage resources—including batteries and hydrogen—can also be charged/refilled and discharged to smooth energy supply and demand. The typical method for determining what resource is used to fulfill the energy demand is “merit order dispatch”. Utilities use this method to dispatch energy

generation sources based on marginal price to minimize the overall cost of meeting demand. However, there are other factors that may constrain merit order dispatch, including minimum generation level for certain resources as well as regulatory requirements related to reliability or sustainability. The model uses a stepwise heuristic-based merit order dispatch algorithm to guide generation and storage resource dispatch. Figure 6 depicts the steps in the dispatch algorithm (top figure), which relies upon separate algorithms to determine storage dispatch (bottom figure) and to ensure that spinning reserve requirements are met. The steps depicted in Figure 6 are described in more detail below.

Figure 6: Algorithm Process Diagram[4]

[4] The algorithm is depicted as a process diagram, in which ovals represent the start/end, rectangles represent a process, parallelograms represent inputs/outputs, and arrows show the relationships between shapes.

First, as depicted by the black line in Figure 7, the average monthly 24-hour electricity load profile for the current month is loaded in from the historical data file from PNM. Then the transmission and distribution (T&D) losses are applied across every hour of the day profile (blue dashed line). The T&D loss rate defaults to the rate used in PNM’s IRP, but the user can adjust the loss rate to explore sensitivities. In Figure 7, the blue line is higher since it requires increased supply to meet the loss due to transmission and distribution. Note that the depicted curves are for September 2025, and there is a different set of data for each month of the simulation.

Figure 7: Apply T&D Losses to Load[A]

Next, the estimated wind generation for that average day, which comes from PNM’s historical data for that month, is subtracted (red line in Figure 8). Then the PV generation for that day is subtracted (yellow line in Figure 8). This is the net utility generation for that day with wind and solar generation applied. It is important to note that when PV generation is added into the curve, the yellow line dips below the zero line. This signals that PV will have to be curtailed or too much energy will be transmitted without a load to use it.

Figure 8: Subtract Wind and PV

24 hour Load Profiles
1
2
3
4
5
6
7
8

9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0
500
1,000
1,500
MW
DAILY ZERO
daily load profile
average day load with losses
September
2,025
24 hour Load Profiles
1
2
3
4
5
6
7
8
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
-500
0
500
1,000
1,500
MW
DAILY ZERO
net day load reduced by wind and solar
average day load after wind applied
daily load profile
average day load with losses
September
2,025

Next the net generation (yellow line) is compared to the amount of generation from the “must run” generation facilities (green line) (Figure 9). “Must run” are those electricity generation facilities that cannot be easily shut down (i.e., nuclear, geothermal). If the must-run generation is greater than the net load amount for any hours of the day, then PV and/or wind must be curtailed so that supply does not exceed demand (in this example, PV is curtailed first and then wind).

Figure 9: Compare Load$_B$ to Must Run Profile

The new yellow line depicted in Figure 10 is the adjusted net load with wind and PV applied and then restricted due to must run generation, which results in an adjusted net load that includes all the must run generation and the PV and wind that is not curtailed. Typically, the curtailed PV and wind would be lost generation since there is no load available to use it. But, as battery storage is applied to the system, some or all of the curtailed wind and PV can be used for recharging the batteries or refueling hydrogen tanks, essentially using free energy for charging storage resources.

Figure 10: Wind and PV Curtailment

The orange-colored area in Figure 11 is the maximum amount of curtailed energy, which is also the maximum amount that can be applied for battery and hydrogen recharge. If there is no need for any battery or hydrogen recharging, then the amount of energy in the orange area is curtailed. Curtailing wind or PV is simply lost generation and something that should be avoided if possible.

24 hour Load Profiles
1
2
3
4
5
6
7
8
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
-500
0
500
1,000
1,500
MW
DAILY ZERO
daily load profile
average day load with losses
average day load after wind applied
net day load reduced by wind and solar
must run generation day profile
September
2,025
24 hour Load Profiles
1
2
3
4
5
6
7
8
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
-500
0
500
1,000
1,500
MW
DAILY ZERO
daily load profile
average day load with losses
average day load after wind applied
must run generation day profile
net generation with PV curtailed
September
2,025

Figure 11: Storage Charging Capacity

Figure 12 summarizes how generation is being used up to this point: the dark blue area is the wind generation applied to load, the yellow area is the PV generation applied to load, the red area is the generation being supplied by must run generation (i.e., nuclear, geothermal), and the light blue area is generation that will be supplied by the dispatchable generation (i.e., coal, CC natural gas, and CT natural gas).

Figure 12: Summary of Generation Resources to Meet Load

Next, the goal is to make use of the curtailed PV and wind through charging battery and hydrogen storage resources (as depicted in the bottom half of Figure 6). Batteries and hydrogen generation typically go through a daily cycle: (1) In the early morning hours when there is increased load batteries and hydrogen can be discharged to help meet load; (2) In the midday hours when load is at its lowest and wind and PV are at their highest production, the extra production can be used to recharge batteries and hydrogen; and (3) In the evening hours during the high demand periods batteries and hydrogen again can be discharged to help meet the load. With this model, no advanced look ahead knowledge is allowed; in other words, while most optimization and resource assessment models have perfect foresight (a projected future which allows adjustments to guarantee they are able to meet the loads), this model only knows what would be known in real life. As such, the model steps through a morning stage, midday stage, and then evening stage of the average day to determine how much storage is discharged in the morning hours, which then determines how much to charge in midday, and then how much is available for discharge in the evenings. To make the best use of storage resources the model does the following. First, it carries over any extra battery storage and hydrogen storage from the previous month. Second, it takes the adjusted load profile (yellow line) and runs it through the merit order dispatch for the morning hours.

24 hour Load Profiles
1
2
3
4
5
6
7
8
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
-500
0
500
1,000
1,500
MW
DAILY ZERO
average day load after wind applied
daily load profile
average day load with losses
must run generation day profile
net generation with PV curtailed
net day load reduced by wind and solar
September
2,025

24 hour Load Profiles
1
2
3
4
5
6
7
8
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
-500
0
500
1,000
1,500
MW
daily load profile
average day load with losses
average day load after wind applied
net generation with PV curtailed
net day load reduced by wind and solar
must run generation day profile
ZERO Baseline
September
2,025

The merit order dispatch tries to meet the adjusted demand by turning on generation facilities as needed based on their cost. The least expensive generation types are used first and as more generation is needed the next least expensive generation type is included. For example, the model starts by using CC natural gas generation and then, if necessary, starts CT natural gas generation to fill the load. If more dispatch than is available from the stack of dispatchable energy is needed, then battery and next hydrogen will be used to help meet supply. Then, because the battery and hydrogen storage may have been discharged in the morning hours, the amount of head room in the battery and hydrogen capacity has to be recalculated. The model will then use as much curtailed PV and wind generation as necessary to recharge the battery and the hydrogen storage during the midday hours. The net load will be readjusted to reflect the addition of wind and PV charging. Finally, the adjusted net profile is run through the merit dispatch algorithm to determine the generation by type for the evening hours. The remaining storage amount in the battery and hydrogen storage at the end of the day is tracked and stored for the next month's calculations. Figure 13 shows a recharge profile for batteries based on available PV and wind that would be curtailed. The red line shows the hour-by-hour charging, and the blue line shows the cumulative charging. In this case, the batteries were fully charged at the end of the midday charging session leaving a full battery set for discharge in the evening hours.

Figure 13: Battery Charging by Hour

Battery Charging by Hour
1
2
3
4
5
6
7
8
9
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0
500
1,000
1,500
2,000
MW
battery charging profile
cumulative battery charging
September
2,025

Figure 14 depicts a resulting resource allocation profile for each hour of the average day in September 2025 and the generation source was being used during those hours. Note that the light green area below the zero line shows the battery charging with curtailed PV. In this case, there was no curtailed PV, all the excess PV was used for battery charging.

Figure 14: Resource Allocation Profile for Average Day in September 2025

Figure 15 shows the resource allocation profile at a later date, June 2026, where there was some curtailed PV shown by the light-yellow area below the zero line. The battery usage is shown by the dark green areas. In this month, the batteries were used in the very early hours and then again in the later evening hours.

Figure 15: Resource Allocation Profile for Average Day in June 2026

After 2040, the PNM IRP stipulates that there will no longer be any natural gas fueled production of energy on the system and hydrogen-ready CTs are converted for hydrogen fuel (dark purple in

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Figure 16). Hydrogen storage is added to the system and becomes part of the early morning and late evening discharge generation package and then the midday charging as well. Figure 16 shows the resource allocation profile for July 2040. In this month, both batteries and hydrogen are recharged during the midday time (light green and pink, respectively) and there is a little PV that is curtailed (light yellow). Moreover, both batteries (dark green) and hydrogen (dark purple) are discharged in the early morning hours and also in the evening hours.

Figure 16: Resource Allocation Profile for Average Day in July 2040

After all the above calculations and adjustments to match load with generation, the model must go through one final adjustment. If the dispatch schedule for each 24-hour period does not have enough spinning reserve to meet the requirement, then the model again adjusts the generation stack. Spinning reserve refers to a certain level of capacity that can quickly be brought online to help utilities to maintain load in the event of unexpected drops in generation and, as discussed in Section 4.4.3, spinning reserve margin adequacy and unmet load are key metrics of system reliability. The model does a cursory tracking of spinning reserve and unmet load in order to provide an estimate of the adequacy of current generation capacity for meeting the projected load. In cases that have lower spinning capacity or more unmet load, those generation combinations can be deemed less desirable and adjusted to reduce one or both of these metrics. The model tries to maintain a minimum amount of spinning capacity, which is typically assigned to the largest generator in the system (note that after 2040, the concept and name will have to be re-examined since there will not actually be any "spinning" capacity available because natural gas CT and CC turbines will all be retired, and thus storage resources will be used to meet reserve capacity after 2040. If available, the next generation type in the stack that is not being used will be brought online at its minimum capacity, while the generation type just below on the stack (i.e., last to be turned on) is reduced by the amount of the minimum capacity of the new generation that was started. This ensures that generation does not exceed the load required, while providing the increased spinning capacity by the size of the new generation facility. This domino method continues until the spinning reserve is met.

5.5.

Base Case Run and Results Calibration

Calibration to PNM's IRP supports validation of the model and provides a base case for constructing resource portfolios and projected load profiles over the planning horizon, against which users can explore the effects of alternative scenarios and resource portfolios on tradeoff metrics, and which can be compared to the base case. The calibration will verify that the algorithms used in the model do an adequate job of dispatching generation on an hourly basis compared to the high-fidelity algorithms that utilities use in real-time. Using these approximate algorithms allows us to run the model very quickly (<1 minute). While extensive model testing was conducted across a wide range of scenario and resource portfolio variables (Appendix B), this section demonstrates how the model performs under the base case (i.e., Scenario 0, Resource Portfolio 0), relative to the IRP. As described in Section 4.4.1, scenarios represent combinations of assumptions about uncertain future economic/demographic and technology/market conditions that affect the feasibility/cost of alternative resource portfolios and the shape/size of projected load profiles. Given the stakeholder advisory group's interest in electrification broadly, and particularly transportation electrification as a potential driver of deep decarbonization across the electricity and vehicle transpiration sub-sectors, Phase 1 scenario exploration focused on the effects of EV adoption on load (other scenario variables—including those related to population and energy intensity growth, hydrogen prices, and natural gas prices—are thus held constant). Scenario 0 is the base scenario and is based on a scenario in PNM's IRP called "Current Trends and Policy,"[5] which represents "what PNM believes to be the most likely set of forecasts" and thus is an appropriate baseline scenario.[6] With respect to EVs, there were ~3,400 EVs in PNM's service territory in 2020. Under this base scenario PNM expects EVs to ramp up from the current 1.26% EV share of new vehicles in 2020 to 9.24% in 2030 and to 16.17% in 2040, resulting in ~127,000 EVs in PNM's service territory [36].

As discussed in Section 4.4.2, resource portfolios represent combinations of generation, storage, DSM, and BTM resources used to meet projected future load profiles over the planning horizon (2021-2045). In Phase 1, two energy storage technology options are included: battery storage, which represents a short duration (i.e., 4-hour) storage technology with a high technology readiness level and thus more certainty around availability and cost, and hydrogen storage, which represents a long duration (i.e., weeks) storage technology with a low technology readiness level and thus less certainty around availability and cost. Resource Portfolio 0 is the base resource portfolio and is based on a resource portfolio in PNM's IRP called "technology neutral," which "considers all technologies (renewables, demand-side resources, storage, and hydrogen CTs) in optimization of future resource

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[5] Note that PNM defines futures as "a set of forecasts that describe the state of the world" and is thus synonymous with what this project refers to as scenarios [33, pp. 72-73].

[6] The following scenario description is provided in the IRP [33, pp. 72-73]: "The 'Current Trends & Policy' future reflects our best estimates of the future state of the world based on the information we have at the time of the IRP's development. Specifically, in this future, we assume: Continued economic and population growth within our service territory consistent with trends as forecast by Woods and Poole, as well as modest levels of incremental customer solar and electrification; Future commodity pricing assumptions based on projections provided by PACE Global that are intended to represent a most likely outcome in gas and electric markets; Technology pricing and future technology cost declines developed based on recent bids provided to PNM and NREL's latest 2020 Annual Technologies Baseline (ATB); and Expiration of federal tax credits for renewable generation based on current sunset dates in the early 2020s."

mix" in order to "identify the least-cost resource plan to meet statutory requirements and PNM's goals."[7]

To build confidence that the model is performing adequately, resource generation capacity and dispatch can be compared across the model simulation for the base case and PNM's IRP results for the corresponding case. Figure 17 depicts the stacked capacities by generation type that are online for each year; the top chart shows the PNM's estimate of capacity by generation type for each year of the simulation and the bottom lower chart shows the model's simulated results for capacity by generation type. It should be noted that the PNM IRP data extends to 2040, but the model runs to 2045 for testing purposes; all trends continue in the last five years, 2041-2045. Moreover, hydrogen generation (dark purple) prior 2040 is actually hydrogen-ready combustion turbines using natural gas as a fuel; these turbines change over to hydrogen fuel in 2040.

Figure 18 depicts the stacked dispatch by generation type for each year of the simulation; the top chart shows PNM's dispatch by generation type for each year in the IRP base case and the bottom lower chart shows the model's simulated results for dispatch by generation type. Notably the simulation depicts the dispatch amount for each month, so it has a different look, but close similarities in peak amounts can be observed. The results are very similar but not exact due to the simplification of the model's dispatch algorithms, which allow for good estimation while also allowing the simulation to run in a reasonable amount of time. Overall, the results suggest that the model's algorithms, described above, are doing an adequate job of estimating the dispatch of the various generation types.

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[7] The following resource portfolio description is provided in the IRP [33, p. 71]: "The 'Technology Neutral' scenario is designed to meet the requirements of the ETA and our own environmental goals at least cost to our customers. Accordingly, this scenario considers only as constraints the legal requirements of the ETA, our own established 2040 goal, the need to preserve reliability, and the engineering limits that govern the operations of the grid. This scenario is intended to demonstrate the lowest cost options to supply the needs of our customers while still achieving the aggressive interim carbon intensity milestones of the ETA as well as meeting the carbon emission-free target of the ETA five years ahead of the statutory schedule. The plan presented by this scenario optimizes our portfolio considering all potential investments that we expect could play a role in meeting our needs in a 2040 carbon emissions-free portfolio, including renewables, storage, energy efficiency, demand response, and hydrogen-ready combustion turbines. Additional emerging technologies may also provide the solutions that would support our transition; we plan to monitor these developments and look for opportunities to incorporate new options in future IRP cycles."

Figure 17: PNM IRP Projected Electricity Generation Capacity by Resource Type (top) and Model Simulated Electricity Generation Capacity by Resource Type (bottom) (2021-2045)

Figure 18: PNM IRP Projected Electricity Generation Dispatch by Resource Type (top) and Model Simulated MW Electricity Generation Dispatch by Resource Type (bottom) (2021-2045)

The tradeoff metrics generated by the model can also be compared to those produced by PNM, to further build confidence in the model. For example, with respect to environmental tradeoff metrics, Figure 19 depicts how the modeled carbon intensity aligns well with the IRP carbon intensity and meets the ETA requirements in 2023, 2032, and thereafter (the differences in early years are explained by the fact that all resources are brought online on January 1 of a given year in the model, as discussed in Section 4.4.2). The model matching of carbon intensity with the IRP also is secondary validation that the dispatch algorithms are doing an adequate job. With respect to costs, conversations with PNM confirmed that the present value of both CapEx and OpEx (depicted in Figure 20) are similar between modeled and IRP results, with differences well explained by the simplified corporate procurement, accounting, and finance approaches employed in the model (e.g., in the model it is assumed that utility owns all resources and CapEx is fully allocated the first year of operation for each new resource).

Figure 19: Base Case Carbon Intensity

Figure 20: Base Case CapEx and OpEx

6.

PHASE 1 MODEL TESTING AND VALIDATION

> “*No* useful model is completely valid, for the model would not be useful unless it were a simplification of reality.”
>
> – Dennis Meadows [44, p. 36] (author’s emphasis).

6.1.

(Degrees of) Validation

Validation is a misnomer when it comes to simulation models. Sterman [45, p. 846] explains:

> “Many modelers speak of model “validation” or claim to have “verified” a model. In fact, validation and verification of models is impossible. The word “verify” derives from the Latin versus-truth; Webster’s defines “verify” as “to establish the truth, accuracy, or reality of.” “Valid” is defined as “having a conclusion correctly derived from premises . . . Valid implies being supported by objective truth.”
>
> By these definitions, no model can ever be verified or validated. Why? Because all models are wrong. … all models, mental or formal, are limited, simplified representations of the real world. They differ from reality in ways large and small, infinite in number.”

Model validation comes not only from testing but from building confidence with stakeholders during the modeling process. Unfortunately, not all modeling processes have the advantage of perfect foresight and access to stakeholders. There are recommended steps for stakeholders to develop confidence in the modeling team (see Appendix B.5).

Model testing should instead be designed to uncover errors so modelers and clients can understand the model’s limitations, improve it, and ultimately use the best available model to assist in important decisions [45, p. 846]. Sargent [46] recommends that ideally these steps should be taken prior to model building.

1. An agreement be made prior to developing the model between (a) the model development team and (b) the model sponsors and (if possible) the users that specifies the basic validation approach and a minimum set of specific validation techniques to be used in the validation process.

2. Specify the amount of accuracy required of the simulation model’s output variables of interest for the model’s intended application prior to starting the development of the model or very early in the model development process.
3. Test, wherever possible, the assumptions and theories underlying the simulation model.
4. In each model iteration, perform at least face validity on the conceptual model.
5. In each model iteration, at least explore the simulation model’s behavior using the computerized model.
6. In at least the last model iteration, make comparisons, if possible, between the simulation model and system behavior (output) data for at least a few sets of experimental conditions, and preferably for several sets.
7. Develop validation documentation for inclusion in the simulation model documentation.

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8. If the simulation model is to be used over a period of time, develop a schedule for periodic review of the model’s validity.

There are diminishing returns to model testing, thus, the goal of this effort is confidence building. All projects are limited in scope, budget, and schedule, Sargent [46] points out the nature of these diminishing returns via a ‘cost’ and ‘value to user’ metric in Figure 21.

Figure 21: Model Confidence (Source: [46])

6.2.

Testing

SD simulation models are a type of software; this project is using software to build software. Testing, in software development, usually involves unit tests, component tests, and integration tests. Testing, however, has been found to find less than 60 percent of errors present in software [47, p. 500]. McConnell [47] reflects that testing: runs counter to the goals of other development activities, never completely proves the absence of errors, does not improve software quality in itself, and assumes that you will find errors.

The project is fortunate to be using Powersim Studio , which has for many years implemented several features in its Interactive Development Environment that guide the development of a simulation model in order to trap some of the most pernicious errors in SD models (and in so doing improve model quality). Studio implements ‘*visual feedback*’ that highlights model construction errors as the model is built:

- Enforcement of time unit consistency – a basic tenant of the SD methodology. This means that each flow must be described in a unit per unit of time.
- Enforcement of complete unit definition – signaling to the modeler that a variable is not well defined. This is often termed ‘dimensional analysis’ or ‘units checking’
- Signals connectivity –showing variable use in equations when the variable is not specifically linked to the equation
- Variable icon variety – using graphics to indicate variable types, e.g., arrays, time dependent, Visual Basic Script, lookups, etc.
- Search capability – to search for invalid and problematic variables
- Run warning – indicating that a model has errors when the simulation is run

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These features aid in catching errors before they are introduced into the model [48]. In addition, the modelers tried to follow best practices in model construction that address naming, layout, dimensional consistency, etc. [40].

Detailed documentation of the testing approach and outcomes is available in consolidated form in Appendix B (the original files in a full-size format are available upon request). Specifically, Appendix B.1 documents testing and outputs across four different scenarios—New Mexico high, medium, and low EV adoption rates as well as average EV adoption projections for the United States—run against the base resource portfolio. Appendix B.2 documents testing and outputs across three resource portfolios that represent the extreme values—zeroing out nuclear; ramping up PV to extreme values; and zeroing out nuclear and natural gas and ramping up PV, wind, battery storage, and hydrogen to extreme values 2022-2045—which are run against the base scenario and can be compared to the base resource portfolio. Appendix B.3 describes integration error checking. Additional sensitivity tests were also run, as documented in Appendix B.4. These sensitivity tests were conducted to examine how the model responds to changes in assumptions about New Mexico's future electric vehicle adoption rate, natural gas and hydrogen commodity prices, various resource portfolio options, as well as discount rates and transmission and distribution loss rates. These tests allowed modelers to confirm visually that the model is performing as expected in calculating key output metrics (i.e., total CO$_2$ emissions, present value of CapEx and OpEx, and MWh of unserved load) given changes in key initial inputs. In addition to the sensitivity testing, the modelers conducted select extreme value testing by introducing large step changes in specific generation capacity assets during the simulation to observe how the model calculates the transient response in the primary output metrics. Specifically, these tests evaluated whether the model responded plausibly given shocks to step changes in generation capacity and looked for unusual, novel, unexpected, or surprise behaviors that might indicate possible errors in the various algorithms embedded in the model [48].

This extensive testing demonstrates that the model is robust to extreme values. Moreover, as discussed in Section 5.5, the model is able to reasonably match projections from PNM's IRP related to generation capacity, dispatch, and tradeoff metrics. Model testing will continue, as Sargent [46] recommends, as the model grows in complexity and scope.

7.

CONCLUSION

This project develops a participatory SD model to represent long term electricity system behavior that is informed by both robust engagement with diverse stakeholders. The resulting model and interface provide a forum for various stakeholders to compare their mental models and a novel methodology for assessing the tradeoffs associated with potential policy and investment strategies to enable decarbonization of New Mexico's electricity sector.

Specifically, the model enables articulation and exploration of three key questions to inform the implementation of decarbonization objectives pursuant to New Mexico's ETA, which mandates 100% zero-carbon electricity by 2050: First, what are the most important uncertainties associated with future scenarios? Second, what are the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements? Third, what are the tradeoffs associated with these alternative resource portfolios and scenarios?

This report documents the development and testing of Phase 1 model, which uses data and projections from PNM's 2020-2040 IRP (and other sources) and returns results calibrated to that plan. Extensive testing of model behavior and results provide confidence that the model is adequately representing one selected scenario from PNM's 2020-2040 IRP.

Phase 2 modeling will introduce feedbacks, time lags, and other projections to allow stakeholders and modelers to simulate tradeoffs associated with alternative decarbonization strategies for New Mexico's electricity sector. In future phases, the model may be extended to other states to improve multi-stakeholder dialogue and decisions around the role of energy storage in integrated grid planning for deep decarbonization.

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APPENDIX A.
MODEL DOCUMENTATION MATRIX

Consistent with SD model documentation conventions [39, 40, 41], the matrix below summarizes the model (matrix source [39], with responses and additions by authors).

Table 5: Model Documentation Matrix

	Explanation	**Responses**
Institutional Setting	Who are the sponsoring organizations, the client, and the modeling group? What circumstances brought them together? What tasks and deadlines were assigned to the modelers? What kinds of communication existed among the sponsor, client, and the modelers, before, during, and after the project?	• Sponsor: U.S. Department of Energy (DOE), Office of Electricity (OE), Energy Storage Program • Stakeholders: New Mexico (NM) Public Regulation Commission (PRC), New Mexico Department of Energy, Minerals, and Natural Resources (EMNRD), Public Service Company of New Mexico (PNM) • Project/Modeling Team: Sandia National Laboratories (Sandia), MindsEye LLC Computing, Bosque Advisors • Communication and Timelines: During the ~8.5 months of Phase 1, the project/modeling team met weekly, met with stakeholders biweekly, and met with project sponsors and partners periodically. These regular project meetings used online meeting platforms, such as Teams, Zoom, and WebEx, depending on the attendees and circumstances. Additionally, the project convened two face-to-face stakeholder workshops for more in-depth model demonstration and discussion.
Purpose and Problem Focus	What was the model built to do? To what real world problems is the model addressed? What phenomena are to be	

explained? What policies are to be tested, or what information is to be generated?

- Problem: Widespread deployment of energy storage coupled with decarbonization of electricity generation offers a critical opportunity to achieve a more sustainable, equitable, and resilient electric power system. Realizing this opportunity for a just transition requires addressing complex technology, social, policy, and market dynamics in electric grid regulatory and investment planning processes through a multi-stakeholder systems approach.
- Purpose: Provide a forum for stakeholders and decision-support to inform implementation of decarbonization objectives via energy storage investments, starting with New Mexico's Energy Transition Act (ETA)
- Goals: Enable articulation and exploration of: (1) the storage-inclusive resource portfolios that would enable New Mexico utilities to meet the ETA requirements (2) the tradeoffs associated with these alternative resource portfolios and (3) the most important uncertainties associated with future scenarios

Method

What modeling paradigm and mathematical techniques have been used in formalizing the system? What limitations are imposed on the model by the techniques used?

- The system dynamics modeling paradigm was used as a framework. Operations research and accepted methods of computing resource dispatch and production costing were also used. The modeling team found no constraints to accomplishing the task due to the paradigm or the software.

Explanation
Responses

Boundaries

Over what period of time does the model attempt to describe the system's behavior? Is this period consistent with the model's purpose? What variables have been included in the model? Which are affected by system behavior (endogenous), and which are independent of system behavior (exogenous)? Are the reasons for variable inclusion/exclusion mode clear? Are the included variables consistent with the purpose and time horizon?

- Spatial scope: PNM's service territory

- Temporal scope: 2021-2045
- Input variables: Planned resource portfolios (generation, storage, demand side management, and behind-the-meter resources), Uncertainties (economic/demographic, market/technology, and policy condition)
- Output variables: Tradeoffs (environmental, utility cost, customer cost, and service quality impacts)

Structure

What form does the network of variable interaction take? How does each variable tie into the system? Are model elements represented in detail or in highly aggregated form?

- The variables included in the model fall into one or more of these categories:
  - o Variables that represent data input (exogenous)
  - o Variables used for calculations (endogenous)
  - o Variables created to build a user interface
  - o Variables used for debugging and model quality checking (typically deleted from the final version)
- The model is constrained by the availability of data. Therefore, the time unit for analysis is one year.

Data

Where did the numbers come from? Are the data adequate to the requirements of the model? Have crude data been refined to meet the model's data requirements? How have ‘soft' variables such as attitudes been handled? What has been done where needed data are not available?

- Data for this model came from three sources: PNM's 2021 IRP (data was both extracted from published material and provided directly by PNM) and the National Renewable Energy Laboratory's publicly available electricity technology cost database and analyses.
- The source data required substantial manipulation to get it into the appropriate format for model input. This consisted of organizing rows and columns so that rows represented time and columns represented individual variables. All input data, with the exception of some constants, was input directly from Microsoft Excel files. Much of the source data was only available as text (PDF files). This required text capture and optical character recognition conversion to Microsoft Excel format.

Conclusions

What is concluded about the system defined by the model? What policies are recommended? To what

	Explanation	**Responses**
	extent have the modeler's conclusions been shaped by the choices of problem, technique, boundary, structure, and data? To what extent do the modeler's base their conclusion on information from mental models? Where they able to answer the questions, they set out to answer?	
Testing	How has the model been tested? What criteria were used to judge model validity? How does model behavior respond to changes in parameters? Is it sensitive to real uncertainties? How robust are the policy conclusions?	• The model was calibrated PNM's IRP to demonstrate that the model results matched the IRP's key results.
Implementation History	Have the modeler's efforts been useful in formulating policy? Who, if anyone, has used the model? What successes and what problems have been encountered by people using the model?	• The model was calibrated PNM's Integrated Resource Plan (IRP) to demonstrate that the model results
Computer Requirements		

How much computer time is necessary to run the model? How much computer memory space does it require? For what computer system was it designed? In what language is it written?

- The model was built in Powersim Studio 10. Powersim Studio only runs under the Microsoft Windows operating system. MS Windows version 10 was the operating system. A user interface was added, and the resulting application runs in Powersim Studio 10 Cockpit. A free version of Cockpit can be found at www.powersim.com.

Documentation

How well does the model documentation allow the above checkpoints to be assessed? Is the writing clear, organized, informative? Are equations available? Are they explained? Is it possible for the model to

- The model is documented internally by:
  - o Dividing the model into modules
  - o The layout of variables in each module
  - o Specific documentation of specific variables
  - o The naming convention used to name and capitalize variables
- Testing can be done through manipulation of the extensive user interface. The interface does not permit changes to model

---

Explanation

Responses

be run and tested by anyone other than the group that wrote it?

equations but does accept changes to assumptions about the future.

Granularity

What is the granularity of the problem context? Is it national, regional, local?

- Climate change is a global problem, and (deep) decarbonization efforts are being shaped by policy decisions at the international, national, regional, and local levels. Given the focus on the U.S. electric power sector, the current focus is on U.S. states because statewide decarbonization mandates are more mature than those at the federal level, although targets have been established at the federal level so these dynamics may change.

Time Un

it
What is the time unit of
the data used? Is it
annual, monthly, daily?

- The time unit for most of the data was year. The model itself uses a time step for integration (dt) of 1 month.

APPENDIX B.
MODEL TESTING

B.1.
Scenario Testing

Table 6 depicts condensed images of model performance across the four EV adoption scenarios, all of which are run using the base resource portfolio. Full size results are available upon request. Scenario 0 is the base case and reflects average EV adoption predictions for New Mexico. Scenarios 1 and 2 are based on low and high EV adoption projections for NM, respectively. Scenario 3 is based on average EV adoption projections for the U.S. Projections for average EV adoption in the U.S. is nearly double than adoptions projected for New Mexico. Row titles refer to a screen in the user interface.

Table 6: Scenario Testing Runs and Results

B.2.
Resource Portfolio Testing

Table 7 depicts condensed images of model performance across three resource portfolios, all of which are run using the base scenario (i.e., average EV adoption rate for NM) and reflect “extreme” values to test model performance. Full size results are available upon request. Resource Portfolio 0 is the base resource portfolio. Resource Portfolio 1 zeros out nuclear 2022-2045. Resource Portfolio 2 ramps PV to extreme values (3000 MW/year) 2022-2045. Resource Portfolio 3 zeroes out nuclear and natural gas and ramps up PV, wind, battery storage, and hydrogen to extreme values 2022-2045. Row titles refer to a screen in the user interface.

Table 7: Resource Portfolio Testing Runs and Results

B.3.

Integration Error Check

The integration method affects the way the simulation results are calculated. The integration method gets its default settings from the Simulation Settings for your component, but you can further customize these to suit your needs. The Euler integration method, which is the default integration method for a new component, will perform one integration step per timestep. However, if your component requires it, you can specify a higher order integration method. Studio supports four different methods of integration, each having a different integration order:

- First order Euler integration
- Second order Runge-Kutta integration
- Third order Runge-Kutta integration
- Fourth order Fixed Step Runge-Kutta integration

Euler is the default method. It calculates the changes in the level variables once per timestep. This means that in complex simulations, it needs a high number of integration steps to be accurate. Increasing the number of integration steps (reducing the size of the timestep) can lead to two different problems. First, it slows down the simulation process, and second, more calculations can cause more round off errors. Worse, however, is that Euler can cause unwanted oscillations to occur in your model.

When you encounter the problems described above, you should switch to a higher order integration method. The second order Runge-Kutta method uses two flow calculations within the given integration step. The reason why this yields a more accurate result - more accurate even than doubling the number of integration steps when using Euler's method - is that the Runge-Kutta method uses a weighted average of the two calculations: the flow during the second part of the integration step is given more weight than the first. The higher order Runge-Kutta methods use even more sophisticated calculation algorithms.

When you define the simulation settings for a model, you specify a time horizon and a timestep. The integration method will perform one integration step per timestep. Thus, to increase the number of integration steps performed during a simulation run, you must reduce the size of the timestep.

As a general rule you can decrease the number of integration steps at least as much as you increase the order of integration. Hence, when going from Euler to the fourth-order Runge-Kutta, do not hesitate to decrease the number of integration steps by at least a factor of four (by increasing the timestep by a factor of four). This usually makes the simulation more accurate - the only problem is that it tends to smooth out sudden changes. This happens because the higher order methods use the value of the flow during the time step to calculate, while Euler's computes the next flow only once, at the beginning of the time step. (Powersim Studio 10, Help, Integration Methods).

Table 8 depicts condensed images of results of the integration error check. Full size results are available upon request. Moving from left to right on the IRP comparison row, note the rounded edges as the integration technique is more refined. Row titles refer to a screen in the user interface.

Table 8: Integration Error Check

B.4.

Additional Sensitivity Testing

The goal of this simple series of tests is to get an idea if the model is performing as expected. The below sensitivity analyses explore how changes to model scenarios (i.e., EV adoption rates, hydrogen prices, natural gas prices), resource portfolios (e.g., PV, wind, and battery), and other variables (e.g., T&D loss rate, discount rate) affect tradeoff metrics (i.e., total CO_2 emissions, present value of CapEx and OpEx, and MWh of unserved load. In addition to the sensitivity tests, several generation and storage capacity tests were conducted. Full size results are available upon request.

Figure 22: Sensitivity Analyses

Discount Rate	Total CO2 Emitted	Total PV	Unserved Energy
rate=2%	950016	13490319446	774.91
rate=4%	950016	11543858576	774.91
rate=6%	950016	10083286005	774.91
rate=8%	950016	8967119733	774.91

Technology Market

1

Discount Rate	Total CO2 Emitted	Total PV	Unserved Energy
Base Case 0	**950016**	**9379227306**	**774.91**
High PV & Wind	**870121**	**9599107263**	**26.98**
High Battery	**943678**	**9484763638**	**496.67**
High PV Wind Battery	**844040**	**9630382164**	**9.01**

Resource Portfolios

1

500,000
600,000
700,000
800,000
900,000
1,000,000
rate=2%
rate=4%
rate=6%
rate=8%

Total CO2 Emitted (tonnes)

5,000,000,000
7,000,000,000
9,000,000,000
11,000,000,000
13,000,000,000
15,000,000,000
rate=2%
rate=4%
rate=6%
rate=8%

Total PV ($)

0
200
400
600
800
1,000
rate=2%
rate=4%
rate=6%
rate=8%

Unserved Energy (MWh)

500,000
600,000
700,000
800,000
900,000
1,000,000
Base Case 0
High PV & Wind
High Battery
High PV Wind Battery

Total CO2 Emitted (tonnes)

5,000,000,000
6,000,000,000
7,000,000,000
8,000,000,000
9,000,000,000
10,000,000,000
Base Case 0 High PV & Wind
High Battery
High PV Wind Battery

Total PV ($)

0
200
400
600
800
1,000
Base Case 0
High PV & Wind
High Battery High PV Wind Battery

Unserved Energy (MWh)

EV Adoption	Total CO2 Emitted	Total NPV	Unserved Energy
Low	934726	9357128720	576.33
Med NM	950016	9379227306	774.91
High NM	967709	9406513175	1736.45
Med US	1009570	9478415894	6442.68

Electric Vehicles

1

Natural Gas	Total CO2 Emitted	Total NPV	Unserved Energy
Low	950016	9238939124	774.91
Base	950016	9379227306	774.91
High	950016	9668058208	774.91

Commodity Prices

Hydrogen Price	Total CO2 Emitted	Total NPV	Unserved Energy
Low	950016	9364283321	774.91
Base	950016	9379227306	774.91
High	950016	9390475254	774.91

Commodity Prices

natural gas
Hydrogen Gas
Losses
Total CO2
Emitted
Total NPV
Unserved
Energy
Losses= 8%
950016
9379227306
774.91
Losses=4%
861389
9226330764
0
Losses=0%
774331
9075623911
0

Load

500,000
600,000
700,000
800,000
900,000
1,000,000
1,100,000
Low
Med NM
High NM
Med US
Total CO2 Emitted (tonnes)
9,000,000,000
9,200,000,000
9,400,000,000
9,600,000,000
9,800,000,000
10,000,000,000
Low
Med NM
High NM
Med US
Total PV ($)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Low
Med NM
High NM
Med US
Unserved Energy (MWh)
0
200000
400000
600000
800000
1000000
Low
Base
High
Total CO2 Emitted (tonnes)
9,000,000,000
9,100,000,000
9,200,000,000
9,300,000,000
9,400,000,000
9,500,000,000
9,600,000,000
9,700,000,000
9,800,000,000
Low
Base
High
Total PV ($)
0
200
400
600
800
1000
Low
Base
High
Unserved Energy (MWh)
0
200000
400000
600000
800000
1000000
Low
Base
High
Total CO2 Emitted (tonnes)
9,350,000,000
9,360,000,000
9,370,000,000
9,380,000,000
9,390,000,000
9,400,000,000
Low
Base
High
Total NPV ($)
0
200
400
600
800
1000
Low
Base
High
Unserved Energy (MWh)
0
200000
400000
600000
800000
1000000
Losses= 8%
Losses=4%
Losses=0%
Total CO2 Emitted (tonnes)
8.9E+09
9E+09
9.1E+09
9.2E+09
9.3E+09
9.4E+09
9.5E+09
Losses= 8%
Losses=4%
Losses=0%
Total PV ($)
0
200
400
600
800
1000
Losses= 8%
Losses=4%
Losses=0%
Unserved Energy (MWh)

Coal Capacity Test – For this test, it is assumed that in 2030, coal capacity is suddenly increased to 1500MW. As a result of this increase, the amount of carbon emitted per year increases significantly beginning in 2030. In addition, the cumulative *present value* is increased possibly due to increased OpEx costs. Finally, with the increased coal capacity, the total unserved load presented in the base case is eliminated.

Figure 23: Coal Capacity Test

PV Solar Capacity Test – For this test, it is assumed that in 2023, PV capacity is suddenly increased to 3,000 MW. Thus, as expected, the amount of carbon emitted per year decreases slightly beginning in 2023. Due to the sudden increase in installed PV capacity, there is a step increase in cumulative *present value* in 2022. Finally, with the increased PV capacity, the total unserved load presented in the base case is reduced in the outyears but not eliminated. Overall, the increase in PV does not have a significant impact on reducing unmet load because PV generation occurs during the lower power demand period of the day. Much of the resulting additional PV generation is curtailed.

Figure 24: PV Solar Capacity Test

Nuclear Capacity Test – For the nuclear capacity test, it is assumed that in 2033, nuclear generation capacity is suddenly decreased to 0 MW. As a result, the amount of carbon emitted per year increases beginning in 2033 but eventually decreases to 0 tons emitted in the outyears as in the base case. Cumulative *present value* does not change substantially between the base and test case. Finally, with the decrease in nuclear power capacity in 2033, we see a dramatic increase in total unserved load in the outyears.

Figure 25: Nuclear Capacity Test

Wind Power Capacity Test – In the wind power capacity test, it is assumed that in 2032, wind generation capacity is suddenly increased to 3,000 MW. As a result, the amount of carbon emitted per year decreases substantially beginning in 2032. As expected, we see a step increase in cumulative *present value* in 2032. Finally, with the increase in wind power capacity in 2032, we see the total unserved load in the outyears drop to 0 MWhs.

Figure 26: Wind Capacity Test

Natural Gas Combined Cycle Capacity Test – For the combined cycle capacity test, it is assumed that in 2030, combined cycle capacity is suddenly increased to 1,500 MW. As a result, the amount of carbon emitted per year remains steady with the increase in natural gas use and does not decrease in the outyears as seen in the base case. As expected, we see a step increase in cumulative *present value* in 2030. Finally, with the increase in combined cycle capacity in 2030, we see the total unserved load in the outyears drop to 0 MWhs.

Figure 27: Natural Gas CC Capacity Test

Battery Capacity Test – For the battery capacity test, it is assumed that in 2031 NM battery capacity is suddenly increased to 3,000 MW. The amount of carbon emitted per year does show a decrease with the increase in battery capacity. However, the decrease is not as dramatic as one would expect with the large amount of battery capacity added because additional renewable resources to charge the battery are not added. In addition, as expected, we see a step increase in cumulative *present value* in 2030. Finally, with the increase in battery capacity in 2031, we see that the total unserved load in the outyears drops to 0 MWhs.

Figure 28: Battery Capacity Test

B.5.

Questions Model Users Should Ask – But Usually Do Not

The following set of questions guided model development, testing, and validation efforts [45, p. 852].

Purpose, Suitability, and Boundary

- What is the purpose of the model?
- What is the boundary of the model? Are the issues important to the purpose treated endogenously? What important variables and issues are exogenous, or excluded? Are important variables excluded because there are no numerical data to quantify them?
- What is the time horizon relevant to the problem? Does the model include the factors that

may change significantly over the time horizon as endogenous elements?

- Is the level of aggregation consistent with the purpose?

Physical and Decision-Making Structure

- Does the model conform to basic physical laws such as conservation of matter? Are all equations dimensionally consistent without the use of fudge factors?
- Is the stock and flow structure explicit and consistent with the model purpose?
- Does the model represent disequilibrium dynamics, or does it assume the system is in or near equilibrium all the time?
- Are appropriate time delays, constraints, and possible bottlenecks taken into account?
- Are people assumed to act rationally and to optimize their performance?
- Does the model account for cognitive limitations, organizational realities, noneconomic motives, and political factors?
- Does the model account for delays, distortions, and noise in information flows?

Robustness and Sensitivity to Alternative Assumptions

- Is the model robust in the face of extreme variations in input conditions or policies?
- Are the policy recommendations sensitive to plausible variations in assumptions, including assumptions about parameters, aggregation, and model boundary?

Pragmatics and Politics of Model Use

- Is the model documented? Is the documentation publicly available? Can you run the model on your own computer?
- What types of data were used to develop and test the model (e.g., aggregate statistics collected by third parties, primary data sources, observation and field-based qualitative data, archival materials, interviews)?
- How do the modelers describe the process they used to test and build confidence in their model? Did critics and independent third parties review the model?
- Are the results of the model reproducible? Are the results “add-factored” or otherwise fudged by the modeler?
- How much does it cost to run the model? Does the budget permit adequate sensitivity testing?
- How long does it take to revise and update the model?
- Is the model being operated by its designers or by third parties?

- What are the biases, ideologies and political agendas of the modelers and clients? How might these biases affect the results, both deliberately and inadvertently?

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